Search for sterile neutrinos at MiniBooNE

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Outline

II: Phenomenology of sterile neutrinos

1. Limitations of models with no sterile neutrinos
   - $\Delta m^2_{sol} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
2. Present constraints on sterile neutrinos in the quasi-two neutrino approximation
3. Combined analysis of accelerator and reactor short-baseline neutrino data for various sterile neutrino models
4. Analysis of supernova neutrino data for various sterile neutrino models
5. Measuring sterile neutrinos via the disappearance of muon neutrinos in a accelerator, short-baseline neutrino oscillation experiment

Combined analysis of SBL experiments

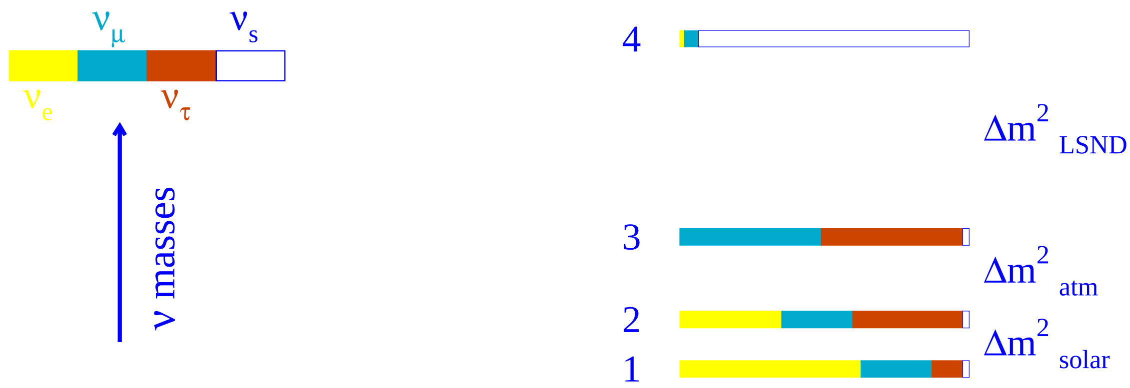
- A motivation for MiniBooNE ν_μ disappearance search. More details on this work in `hep-ph/0305255`
- Combined analysis because SBL experiments
  1. ν_μ disappearance (CCFR84, CDHS)
  2. $\bar{\nu}_e$ disappearance (Bugey, CHOOZ)
  3. $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance (LSND, KARMEN)

  probe same Δm^2's and matrix elements:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

- Combined analysis of past SBL data can tell:
  1. whether one can consistently explain the solar, atmospheric, LSND, and the null short-baseline results via oscillations
  2. what are the favored values from past experiments for Δm^2_{41}, $U_{\mu 4}$, Δm^2_{51}, $U_{\mu 5}$, etc.
     $\Rightarrow$ what are the expectations for ν_μ disappearance at MiniBooNE? Can be at the 10-20% level ($\gg \nu_e$ appearance), and for accessible Δm^2 values
- Oscillation physics reach of $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_{\not\mu}$ searches is quite complementary

Results on (3+1) models



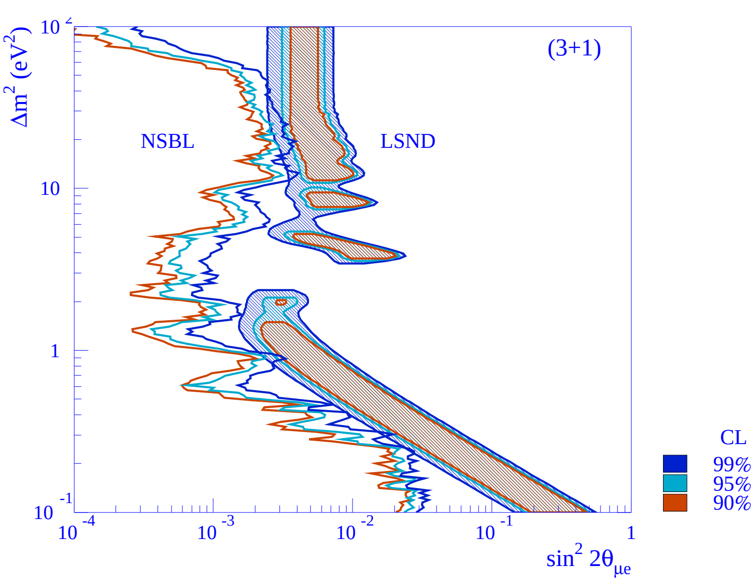
- $\Delta m^2_{43} \gg \Delta m^2_{32} \gg \Delta m^2_{21}$: two-neutrino approximation is satisfied. Can define:

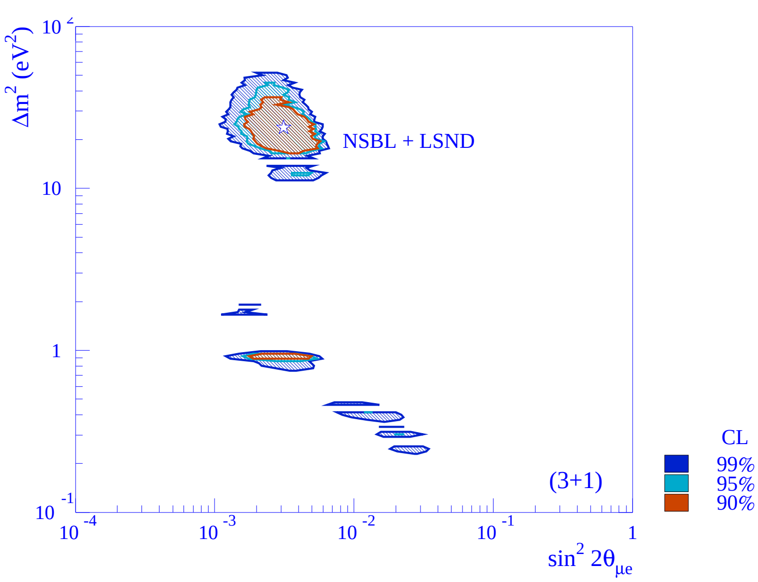
$$\Delta m^2 \equiv \Delta m^2_{41}, \qquad \sin^2 2\theta_{\mu e} \equiv 4U^2_{e4}U^2_{\mu 4}$$

- Two analyses:

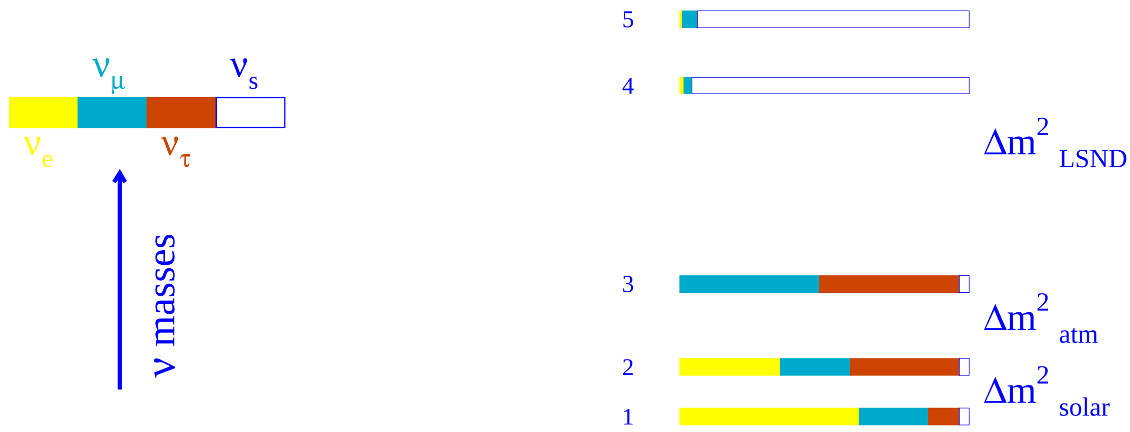
1: Compatibility of SBL data in (3+1) by looking at LSND and NSBL allowed regions separately

2: Best-fit values in (3+1) by combined analysis (assumes statistical compatibility)





Results on (3+2) models



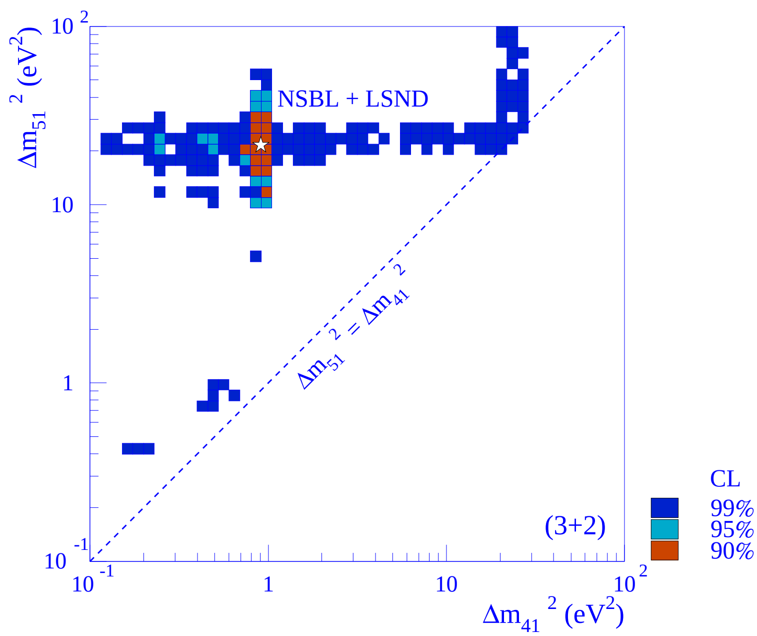
- Six parameters probed: Δm^2_{41}, U_{e4}, $U_{\mu 4}$, Δm^2_{51}, U_{e5}, $U_{\mu 5}$
- More than one Δm^2 in the oscillation probability
- Instead of $\sin^2 2\theta_{\mu e}$ limit, use NSBL to constrain the $\bar{\nu}_\mu \to \bar{\nu}_e$ probability averaged over the LSND L/E distribution:

$$p_{LSND} \equiv \langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle_{LSND}$$

- (3+2) models describe SBL data (and LSND oscillations) significantly better than (3+1)

Best-fit values for mass splittings in (3+2):

will update soon with NOMAD $\nu_\mu \to \nu_e$ results



IV: The BooNE neutrino flux

1. Overview of the BooNE neutrino beamline

2. Analyses of non-MiniBooNE pion production data to understand the MiniBooNE neutrino flux

3. The magnetic focusing horn and its impact on the neutrino flux

4. Expected neutrino fluxes from Monte-Carlo simulations

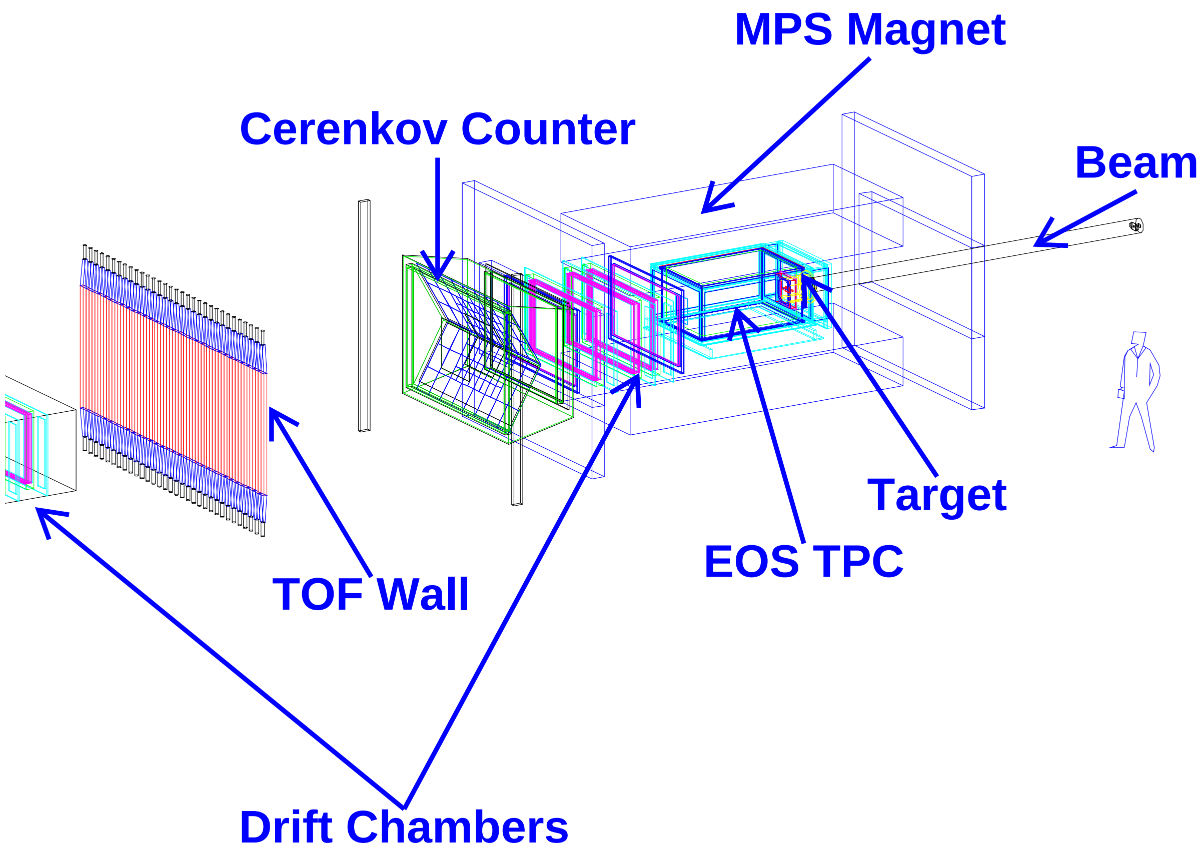
Motivation for non-MiniBooNE pion production analyses

- Uncertainty in MiniBooNE ν_μ flux dominated by uncertainty in $\pi^\pm$ production in p-Be interactions
- Understanding the flux and its associated systematic uncertainties is key in almost all MiniBooNE analyses: oscillation, cross-section, exotics analyses
- $\pi^\pm$'s we care the most: $p_\pi = 1-4$ GeV/c, $\theta_\pi < 200$ mrad
- So far we have flux estimates from hadronic models with large uncertainties and/or optimized for energy ranges not relevant to MiniBooNE
- In MiniBooNE, we are working on tuning our flux estimates based on various sources of non-MiniBooNE data:

  1. Compilation and reanalysis of existing $\pi^\pm$ production cross-sections
  2. Extracting cross-sections from BNL E910 data on thin Be target. (Published results cover only $p < 1.2$ GeV/c)
  3. Extracting cross-sections from CERN HARP data on thin and thick Be targets, at precisely Booster proton energies

- Will need $K^\pm$, K_L^0 cross-sections as well for the the intrinsic ν_e background estimates for the $\nu_\mu \rightarrow \nu_e$ ($\Rightarrow$ HARP, E910)

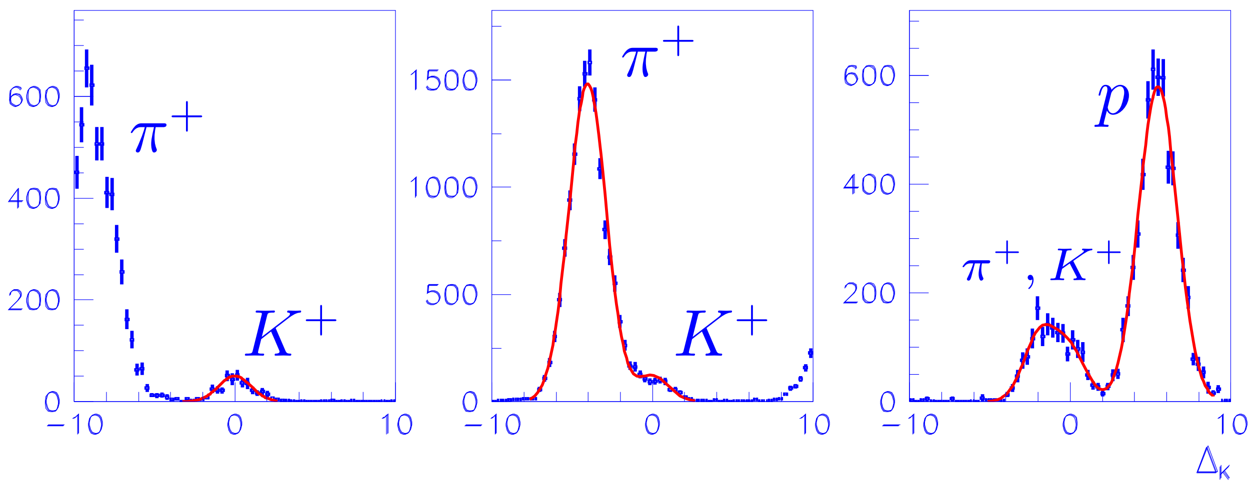
BNL E910



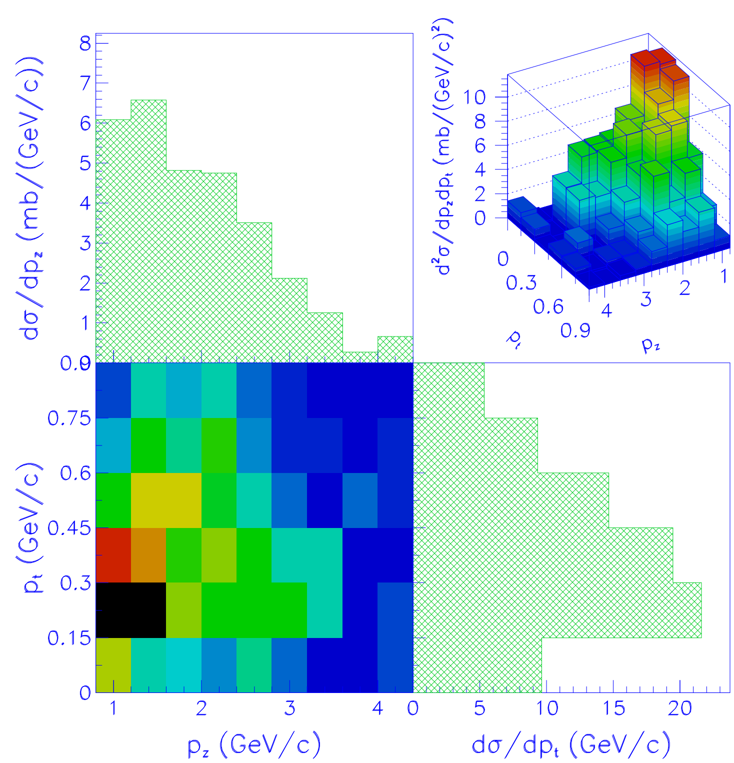
- Data exists for 6.0 and 12.5 GeV/c proton beam momentum on 5% λ_I Be target
- Subdetectors give Particle ID at all pion momenta and angles of relevance to us:
  1. dE/dx information from TPC $\Rightarrow p_\pi < 1$ GeV/c, $p_\pi > 3$ GeV/c
  2. velocity information from TOF wall $\Rightarrow p_\pi < 3$ GeV/c
  3. Light in Cherenkov threshold detector $\Rightarrow p_\pi > 3$ GeV/c
- Preliminary K^+ analysis to draw from, for $\pi^\pm$ analysis
- Bi-weekly meetings held with E910 people. Goal: have E910 cross-sections in the beam MC this summer

BNL E910 K^+ analysis

- Cut on dE/dx and Cherenkov photons to reject pions and protons, fit K^+ yields using TOF residuals distributions, taking into account contamination:



Preliminary results on $d^2\sigma/dp_z dp_t$ for the inclusive process $p + Be \rightarrow K^+ + X$ at 12.5 GeV/c



GEANT4-based beam MC

- Motivation for using G4 instead of G3 for the MiniBooNE beam MC is its capability of being easily interfaced with a user-defined hadronic model. Applications:

    1. Use external data to model p-Be inelastic interactions (and others), and therefore to predict the MiniBooNE ν_μ, ν_e flux
    2. Predict uncertainties and energy bin-to-bin correlations for the ν_μ, ν_e flux, based on experimental data

- Code uses the same G3 BooNE geometry files, and can also run with HARP geometry files

- Four production physics models currently implemented:

    1. MARS
    2. Sanford-Wang parametrization of ZGS $\pi^\pm$ production data
    3. GFLUKA
    4. "Customizable" Sanford-Wang parametrization for $\pi^\pm$, for beam MC tuning and understanding of flux systematic uncertainties

- Code framework does not require any major modifications to link additional physics input on $p, \pi^\pm, K^\pm, K_L^0$ production for primary p-Be interactions, such as:

    1. updated and MiniBooNE-specific S-W fits
    2. E910
    3. HARP

MiniBooNE GEANT4 Beam Montecarlo - Mozilla {Build ID: 2002051013}

MiniBooNE GEANT4 Beam Montecar... | Beam Normalization Task Force Page | (Untitled)

BooNEG4Beam

the status of software development for a MiniBooNE Beam MonteCarlo written in Geant4

News, Status and Results

- 04-Jul-2003: BooNEG4Beam v1.3 in CVS.
- Results on the neutrino flux from G4, for three different physics models (v1.1)
- Validation of the code, by comparing BooNEG4Beam with the GEANT3 beam MC, for both the MARS and GFLUKA models (v1.1)
- BooNEG4Beam picture gallery
- To-do list , as of 04-Jul-2003

Useful Information

- Output ntuples variables key can be found here
- List of all commands available to the user in the jobOptions file can be found here (MiniBooNE specific commans are in the /boone/ subdirectory)
- The currently implemented tracking thresholds in range and energy for various particles and materials can be found here
- List of known GEANT4 bugs affecting MiniBooNE

BooNEG4Beam Releases

- **Release R1-3** : source code in CVS (posted 04-Jul-2003)

  Main changes and bug fixes are:

  - more commands available in the jobOptions file, to characterize the primary beam description and the horn magnetic field
  - flag to fill ntuple 3000, containing information about all particles relevant for neutrino production after the cone collimator. Useful input for the NUSPEK program.
  - Added KaonZeroLong production in p-Be interactions. The list of secondaries produced is now: protons, charged pions, charged kaons, klongs
  - Muon polarization in muon rest frame is now stored in ntuple 1000. The polarization is calculated from the parent pion and muon momentum, for a (V-A) interaction.
  - Fixed bug for which muons capturing at rest were giving nues and not numus.
  - More details can be found in the release notes

Beam normalization task force and G4 certification

- Measured neutrino interaction rate is about 1.6 times higher than what predicted by current MARS/NUANCE/detMC/AF analysis chain

- Task-force extablished to verify all intermediate steps in the data/MC comparison

- Beam group activities:

  1. bug hunting
  2. comparison of results from alternative simulation tools
  3. improving simulation tools
  4. comparison of results from alternative physics models

- See: `http://www-boone.fnal.gov/beam_norm/`

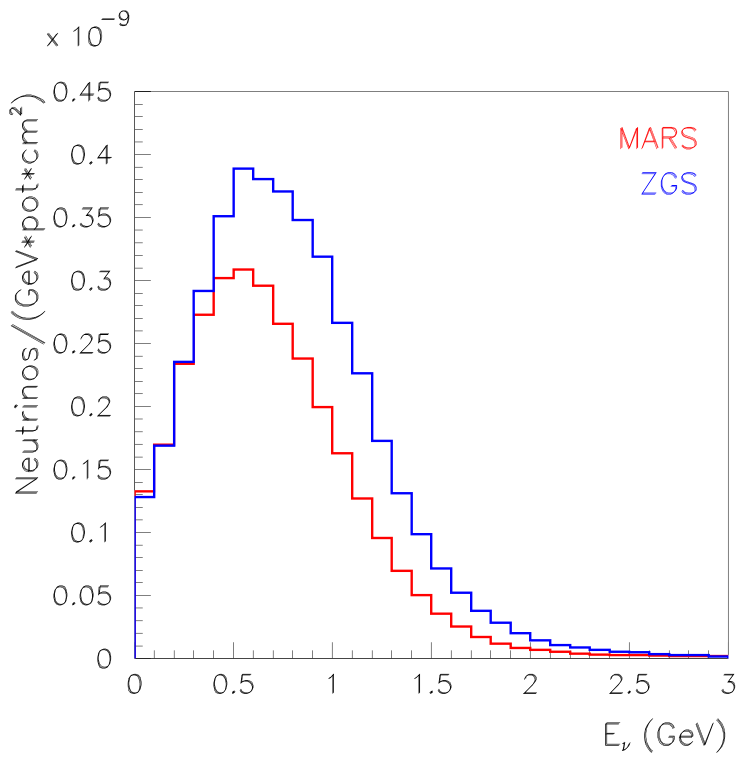
- Working on the above aspects for the G4 beam MC

- G4 certification progressing well (no known bugs at this time), thorough note documenting it is in the works

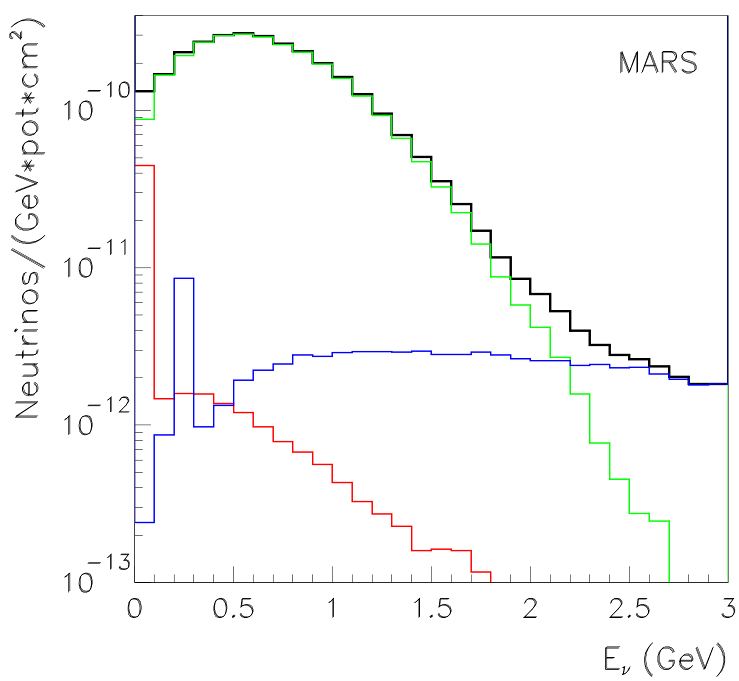
Expected G4 neutrino fluxes

- Dependencies on production model:

Model	$\phi((pot \cdot cm^2)^{-1})$
MARS	$3.06 \cdot 10^{-10}$
ZGS	$4.15 \cdot 10^{-10}$



ν parent	$\phi((pot \cdot cm^2)^{-1})$	Frac (%)
μ	$5.69 \cdot 10^{-12}$	1.9
π	$2.92 \cdot 10^{-10}$	95.7
k	$7.50 \cdot 10^{-12}$	2.4
Total	$3.06 \cdot 10^{-10}$	100.0

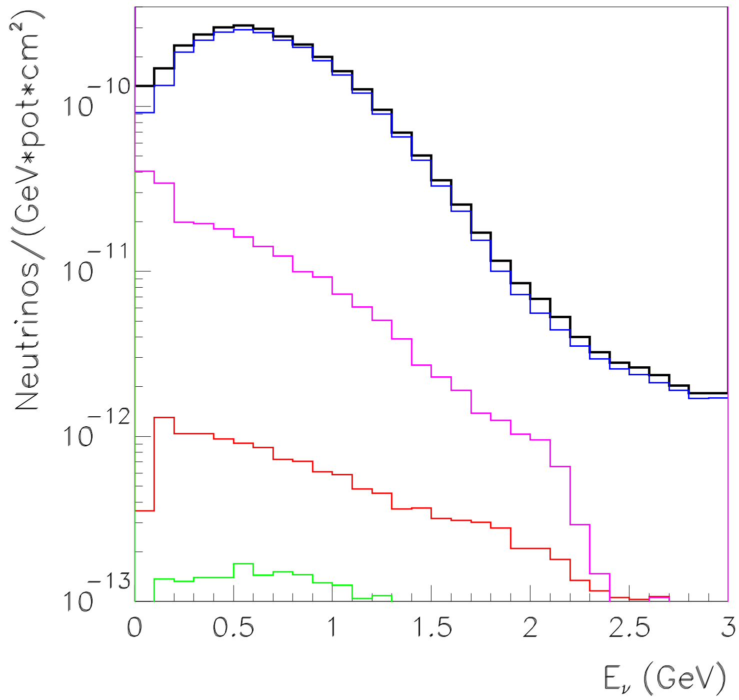


Expected G4 neutrino fluxes (cont'd)

- Flavor composition in ν and $\bar{\nu}$ running mode:

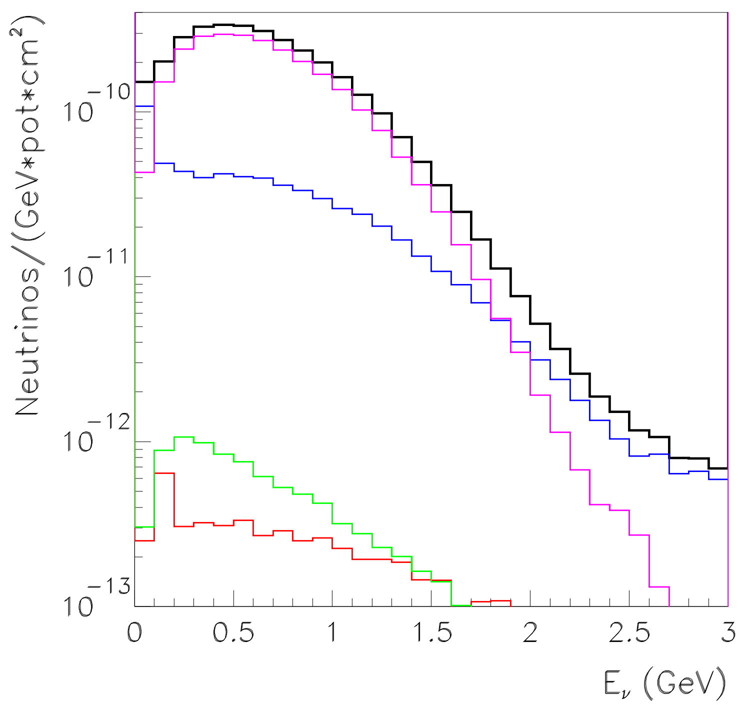
ν running mode:

ν type	$\phi((pot \cdot cm^2)^{-1})$	Frac (%)
ν_e	$1.34 \cdot 10^{-12}$	0.4
$\bar{\nu}_e$	$2.48 \cdot 10^{-13}$	0.1
ν_μ	$2.81 \cdot 10^{-10}$	92.0
$\bar{\nu}_\mu$	$2.29 \cdot 10^{-11}$	7.5
Total	$3.06 \cdot 10^{-10}$	100.0



$\bar{\nu}$ running mode:

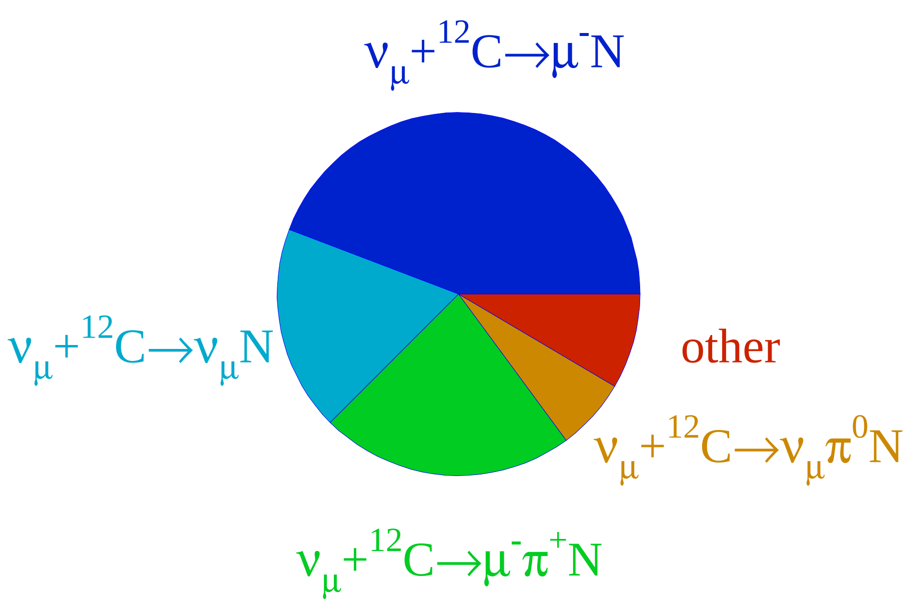
ν type	$\phi((pot \cdot cm^2)^{-1})$	Frac (%)
ν_e	$5.28 \cdot 10^{-13}$	0.2
$\bar{\nu}_e$	$8.96 \cdot 10^{-13}$	0.3
ν_μ	$6.12 \cdot 10^{-11}$	18.5
$\bar{\nu}_\mu$	$2.66 \cdot 10^{-10}$	81.0
Total	$3.28 \cdot 10^{-10}$	100.0



V: Neutrino interactions in the $\sim$1 GeV energy range

1. Overview
2. Nuclear effects
3. The quasi-elastic interaction
4. Other neutrino interactions
5. Expected neutrino cross-sections as a function of energy and final state kinematics from Monte-Carlo simulations

- Assume cross-sections for ν_μ disappearance analysis
- Final state kinematics: need accurate fractions of interaction types, and $d^2\sigma/dE_\mu dE_\nu$ for $\nu_\mu n \to \mu p$ and all other important processes



V: Event reconstruction in MiniBooNE

1. Overview of the MiniBooNE detector
2. The MiniBooNE optical model
3. Event vertex reconstruction
4. Track direction recosntruction
5. Visible energy reconstruction
6. Final state reconstruction

VI: Event selection for the ν_μ disappearance analysis

1. Physics considerations for the event selection criteria
2. Description of the event selection criteria
    - PMT hit coarse time information
    - PMT hit fine time information
    - PMT hit spatial topology
3. Efficiency and biases in the event reconstruction and selection

VII: The ν_μ disappearance analysis

1. Overview
   - How to do the analysis: look for neutrino energy-dependent shape distortions of the observed neutrino rate distributions with respect to the no-oscillation expectation
   - Advantages of a normalization-free analysis
   - Observables used
2. Systematic uncertainties
3. The oscillation fitting code
4. MiniBooNE sensitivity to $\nu_\mu \rightarrow \nu_{\not\mu}$ oscillations
   - Sensitivity in the quasi-two neutrino approximation
   - Sensitivity in more general neutrino models
5. Data sample used in the analysis
6. Results
   - Compatibility between data and the no-oscillation hypothesis
   - Constraints in neutrino mass and mixing parameter space
7. The future: expected improvements

Observables used in the analysis

- One nice possibility (e.g. K2K) is to combine:

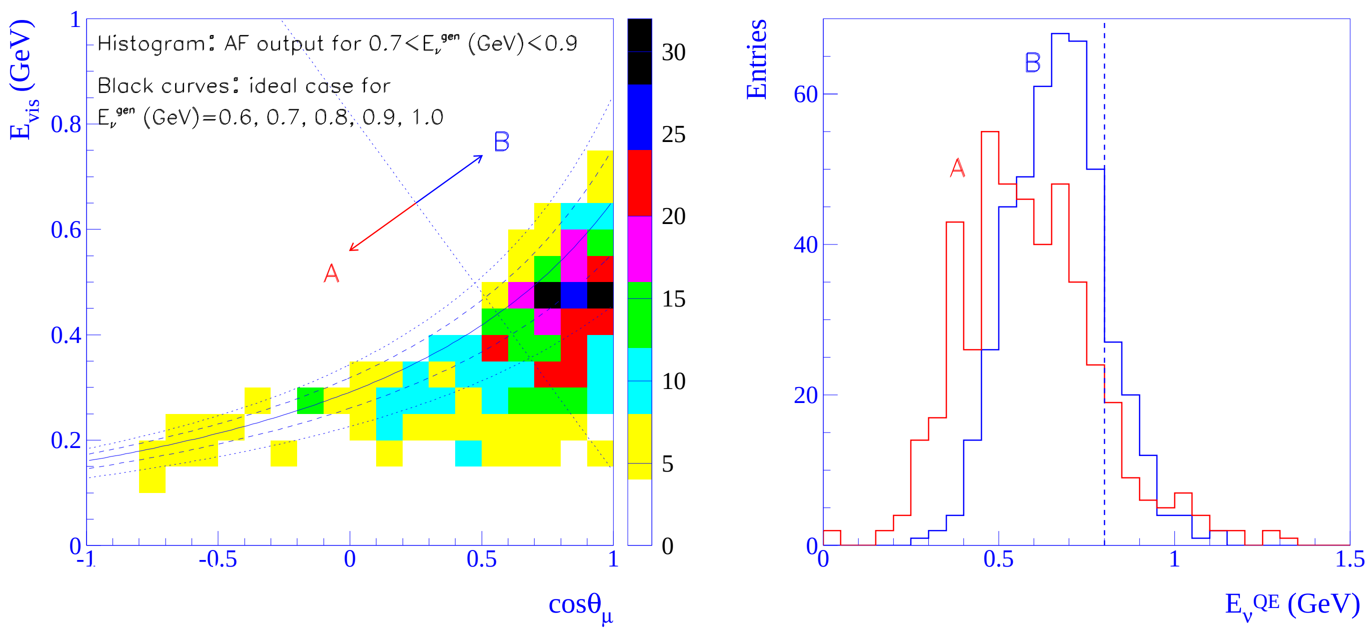
  1. observed muon energy E_μ
  2. observed angle θ_μ wrt to incoming ν direction

  into one neutrino energy estimator. For a perfect detector, no Fermi momentum, and for a QE interaction:

$$E_\nu^{QE} \equiv \frac{1}{2} \frac{2ME_\mu - m_\mu^2}{M - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu} = E_\nu$$

  where $E_\mu = E_{vis} + m_\mu + E_{subC}$

- Another possibility is to do the analysis as a function of both observables $(E_\mu, \cos\theta_\mu)$ separately. For real detector (MiniBooNE) and QE events only:

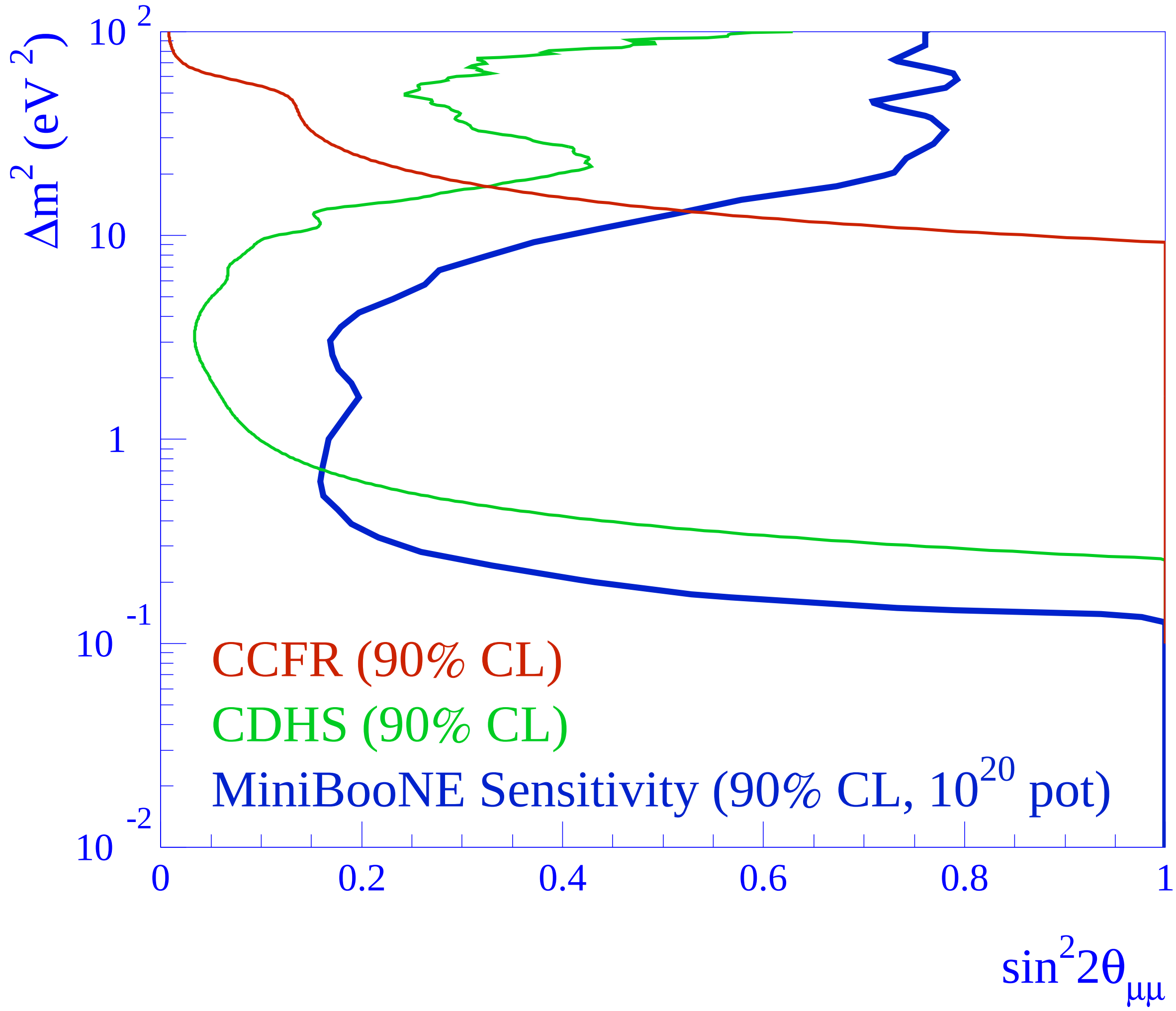


Systematic uncertainties

- Working on first guesses at flux and cross-section energy shape uncertainties
- How to treat systematic uncertainties in the analysis? Some possibilities that have been used in similar disappearance analyses (χ^2 analysis as example):
  1. Absorb systematic errors in the error matrix (e.g. CCFR84, CDHS)
  2. Treat parameters describing systematic uncertainties as fitting parameters with additional constraint terms in the χ^2 (e.g. CHOOZ, Bugey, K2K)
  3. Average χ^2 sampled over many random trials, weighted according to the probability density distribution of the systematic parameters (e.g. K2K)

ν_μ disappearance sensitivity (qualitative)

- Two-neutrino approximation:



- MiniBooNE can extend low Δm^2 reach